Publications of the FTIA
25/2023

Finnish Transport Infrastructure Agency

DIGI RAIL

Funded by the European Union
NextGenerationEU

Public Mobile Radio Networks Suitability for ETCS Traffic

Simon Indola, Peteveikko Lyly, Mohamed Shamekh, Jean Danielsbacka, Heikki Kaaranen

Public Mobile Radio Networks Suitability for ETCS Traffic

Publications of the FTIA 25/2023

Finnish Transport Infrastructure Agency
Helsinki 2023

Online publication pdf (www.vayla.fi)
ISSN 2490-0745
ISBN 978-952-317-061-6

Funded by
the European Union
NextGenerationEU

Finnish Transport Infrastructure Agency
P.O.Box 33
00521 HELSINKI
tel. 0295 343 000

Simon Indola, Peteveikko Lyly, Mohamed Shamekh, Jean Danielsbacka, Heikki Kaaranen: Public Mobile Radio Networks Suitability for ETCS Traffic. Finnish Transport Infrastructure Agency Helsinki 2023. Publications of the FTIA 25/2023. 36 pages. ISSN 2490-0745, ISBN 978-952-317-061-6.

Abstract

The European railway industry and operators are currently specifying the ERTMS related Future Radio Mobile Communication System (FRMCS). This document contains background information, a test arrangement description and test results after verifying the public 4G/5G mobile network suitability of carrying ETCS traffic reliably. The tests were performed in Finland by utilising the public mobile network operators: Elisa, Telia and DNA.

Simon Indola, Peteveikko Lyly, Mohamed Shamekh, Jean Danielsbacka, Heikki Kaaranen: Julkisten matkaviestinverkkojen sopivuus ETCS-liikenteeseen. Väylävirasto. Helsingfors 2023. Väyläviraston julkaisuja 25/2023. 36 sivua. ISSN 2490-0745, ISBN 978-952-317-061-6.

Avainsanat: rautatiet, matkaviestinverkot, liikenne

Tiivistelmä

Euroopan rautatieteollisuus ja operoijat määrittelevät parhaillaan ERTMS:n osaksi kuuluvaa radioyhteysjärjestelmää (FRMCS). Tässä dokumentissa kuvataan taustatiedot, testijärjestelyt ja testitulokset koskien julkisten 4G/5G-matkaviestinverkkojen sopivuutta ETCS-liikenteen luotettavaan siirtämiseen. Testit suoritettiin Suomessa käyttäen Elisan, Telian ja DNA:n matkaviestinverkkoja.

Simon Indola, Peteveikko Lyly, Mohamed Shamekh, Jean Danielsbacka, Heikki Kaaranen: De offentliga mobila nätverkens lämplighet för ETCS-trafik. Trafikledsverket Helsinki 2023. Trafikledsverkets publikationer 25/2023. 36 sidor. ISSN 2490-0745, ISBN 978-952-317-061-6.

Sammanfattning

The European railway industry and operators are currently specifying the ERTMS related Future Radio Mobile Communication System (FRMCS). This document contains background information, a test arrangement description and test results after verifying the public 4G/5G mobile network suitability of carrying ETCS traffic reliably. The tests were performed in Finland by utilising the public mobile network operators: Elisa, Telia and DNA.

Foreword

This report was commissioned by the Finnish Transport Infrastructure Agency and authored by Simon Indola from Fintraffic Oy, Peteveikko Lyly from the Finnish Transport Infrastructure Agency, Mohamed Shamekh from Omnitele Oy, Jean Danielsbacka from Cinia Oy and Heikki Kaaranen from Proxion Oy.

In Helsinki, April 2023

Finnish Transport Infrastructure Agency
Digirail and Procurement of Traffic Control

Contents

1 Abbreviations & Terms

1.1 Abbreviations

3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile Network
5G	5th Generation Mobile Network
APN	Access Point Name
BDS	BeiDou Navigation Satellite System: Chinese origin
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication System
FTIA	Finnish Transport Infrastructure Agency
GALILEO	European Global Satellite Navigation System
GLONASS	Global Navigation Satellite System: Russian origin.
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GSM	Global System for Mobile communications
GSM-R	GSM for Railways
IP	Internet Protocol
JKV	Finnish national railway traffic management system (suom. Junien kulunvalvontajärjestelmä)
LTE	Long Term Evolution
MA	Movement Authority (ETCS message)
MPLS	Multiprotocol Label Switching
MTU	Maximum Transmission Unit
OBU	On-Board Unit
PBX	Private Branch eXchange
PSTN	Public Switched Telephone Network

RAN	Radio Access Network
RBC	Radio Block Centre
RSRP	Reference Signal Reflected Power
RSRQ	Reference Signal Reflected Quality
SINR	Signal-to-Interference plus Noise Ratio
SLA	Service Level Agreement
TCP	Transmission Control Protocol
TRAFICOM	Finnish Transport and Communications Agency
UIC	International Union of Railways

1.2 Terms

Digirail Network and Radio Team: a part of the Digirail project organisation concentrating on ETCS network and radio communication. Team members: Simon Indola (leader) / Fintraffic Oy, Jean Danielsbacka / Cinia Oy, Mohamed Shamekh / Omnitele Oy, Peteveikko Lyly / FTIA, Heikki Kaaranen / Proxion Oy.

ETCS Traffic: signalling traffic occurring between the RBC (Radio Block Centre at the traffic management centre) and OBU (on-board computer in the railway vehicle). ETCS traffic message formats, parameters and message sequences are defined and all data is available at: https://www.era.europa.eu/system/files/2022-11/index004_-_subset-026_v230.zip

TCP/IP: protocol combination transferring IP packets between two computers. The TCP protocol contains an acknowledgement mechanism where each received IP packet is acknowledged, thus increasing the reliability that the data has been received and processed correctly. The TCP as protocol has been specified here: https://www.ietf.org/rfc/rfc793.txt

Moving Block system: ETCS implementation where the moving railway vehicle has a security area both at the front and back of the vehicle. The security area size depends on vehicle speed and railway traffic security instructions. In terms of traffic capacity, a smaller Moving Block increases track capacity (more trains) and requires more accurate traffic management.

VIRVE: Public Authority Network (Finnish "Viranomaisverkko"). A nationwide private shared RAN access-based network used by the police, army, fire brigade, certain medical personnel, and other official bodies.

QoS: Quality of Service: method(s) to classify connections the way they are serving the transferred traffic the best possible way, but not consuming too many network resources.

2 Scope

2.1 The Finnish Mobile Network Landscape

Finland has three mobile network operators (MNOs) offering nationwide coverage, which are Elisa Oyj, Telia Oyj and DNA Oyj. The Finnish operators currently offer their customers "all you can eat" (unlimited data transfer) subscriptions at a fixed price.

With a population of 5.5 million, the Finnish MNOs combined have around 9 million mobile subscriptions, and annual churn (people changing mobile provider) is currently around 15-18%. Finland is a sparsely populated country (approx. 18 persons per km2), thus the rural broadband implementations have been based on mobile coverage. Legacy PSTN lines have been mostly dismantled and replaced either by Wireless Local Loop solutions (private customers) or with advanced Mobile PBX solutions (corporate customers).

All Finnish mobile networks are controlled in terms of coverage, capacity, and operating quality by Traficom (Finnish Telecom Authority).

2.2 Finnish Mobile Networks and the Railway Landscape

In Finland, ERTMS/FRMCS evolvement and migration is executed under the authority of the Digirail -project (www.digirata.fi). This project is divided into several sub-projects dealing with specialised ERTMS/FMRCS areas. This White Paper describes how the Digirail Network and the Radio Project Team approached the radio communication of ETCS Level 2/3 usage, where trains send and receive traffic control information using ETCS signalling by using radio connection(s).

Finland is in an exceptional position since the Finnish railway network does not use GSM-R at all. The GSM-R network was dismantled several years ago, and the frequencies were freed, but they are not in active use. Rather than using GSM-R, railways currently utilise the TETRA-technology-based nationwide public authority network (VIRVE) for voice communication. This arrangement is based on a derogation and is a short-term interim solution as FRMCS can soon be deployed.

The current Finnish national railway traffic management system (JKV) is based on the usage of balises (an electronic beacon or transponder), which is similar to ETCS Level 1, delivering the necessary data from the trackside to the railway vehicles. Voice connections (standard calls and Railway Emergency Calls) are delivered over the VIRVE network, which is shared TETRA network used by public safety users.

Specification bodies have been studying in recent years how to evolve from GSM-R technology towards more modern radio connections, since GSM-R has its limitations, and since GSM-R is considered a drifting technology, there will be future challenges concerning equipment and spare parts availability. In addition, GSM-R data transfer capabilities are very limited, especially in cases where there are many users performing transactions.

GSM-R is a dedicated network with a limited user amount in practice (as it is not available for the general public). Based on this, a very natural approach in specification bodies has been that the FRMCS network should also be dedicated in nature. This approach, however, may lead to high investment needs, leading to it becoming a costly solution. Even more problematic, is that by using a dedicated radio network with specialised radio characteristics and hence unique requirements, the deployment will be delayed for many years due to the unavailability of suitable chipsets.

Another approach could be to use public mobile networks instead. This raises several questions:

A. Cybersecurity: can the public mobile networks deliver an adequate service level in terms of security?
B. Capacity: can the public mobile networks offer adequate capacity to deliver ETCS traffic?
C. Coverage: can the public mobile networks offer adequate coverage to ensure that railways are covered for ETCS traffic needs?
D. Quality: can the public mobile networks offer adequate quality to transfer ETCS traffic reliably?

A Digirail Radio Team studied these above listed issues carefully during 2021-2022. Following the study, the following highlights can be outlined:

A. Cybersecurity in public mobile networks: in Finland, this is observed and controlled by public authorities and all operators follow state-of-the-art practices guaranteeing network and subscription security from their point of view. Additional security can be achieved by applying end-to-end security procedures (inside the radio channel) on an application level. Overall cybersecurity related to ETCS L2/L3 was also analysed by the Digirail-project's Cybersecurity subgroup.
B. Public mobile network capacity: when studying statistics and license conditions, the capacity should not be a problem. However, this is something to be verified by testing.
C. Public mobile network coverage: when studying statistics and license conditions, the coverage should not be a problem. However, this is something to be verified by testing.
D. Public mobile network quality: in practice, all public mobile network data subscriptions use QoS profile Best Effort, meaning that available bandwidth is distributed to all users and thus the available bandwidth per subscriber varies from 0 to N Mb/s. This environment is not suitable to transfer ETCS traffic as such, but all public mobile networks support subscriber profiles where some guarantees for bandwidth availability can be set. This parameterisation is discussed in section 4 of this document.

The above conclusions could be drawn as a result of the Digirail testing and verification program. The target of the program was to evaluate whether the public mobile networks are suitable for ETCS traffic delivery. The testing arrangements are discussed in section 5 of this document and the results are presented in section 6.

3 Common Radio Connection Challenges

This section briefly discusses the common radio connection challenges which should be considered in the context of railways. A pure radio connection is unstable as such, and many environmental factors may influence its functionality.

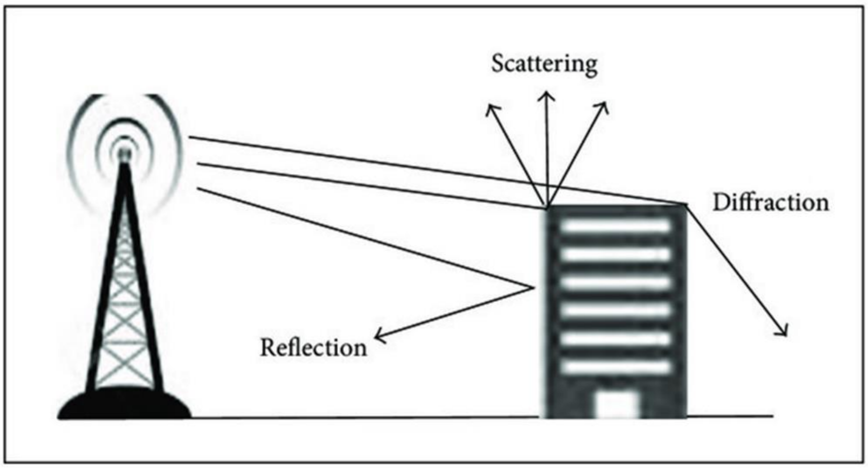
When considering present day public mobile networks, there are many technical methods which improve the stability of the radio connection from the user and network point of view. These improvements have been presented as mobile network generations (2G, 3G, 4G, 5G etc.).

2G technologies (GSM-R is one of these) provide a basic radio connection with basic error-correction mechanisms. Since all transmissions and users are separated in time, simple mechanisms are enough to guarantee the connection functionality. The other generations use alternative methods to transfer signals between the user terminal and network and these methods require more sophisticated ways and algorithms to guarantee radio connection functionality and stability.

To make it simple, it can be stated that technologies like 2G require stable power to maintain radio connection properly. Technologies like 4G and 5G contain sophisticated mechanisms which can compensate for changing power and connection quality levels.

The following sub-sections shortlist some environmental factors impacting radio connection quality, usability, and reliability.

3.1 Reflections



Picture source: https://doi.org/10.1155/2017/3932487

Figure 1. Reflection types.

As Figure 1 above suggests, there are three types of signal "reflection", namely reflection, scattering and diffraction. Practically, these are present everywhere within the built environment.

To simplify: the higher the radio frequency is (MHz, GHz), the easier it reflects, diffracts, and scatters. The lower the radio frequency is, it passes through buildings to some extent rather than reflects.

In FRMCS, the planned frequency areas for dedicated networks are around 900 MHz (GSM-R replacement) and 1900 MHz. The higher frequency area, in particular, may suffer from reflections if the radio network is not planned properly. For railway traffic, the places where reflection may occur are railway stations which have a densely built environment, for example Finland's Helsinki railway station, the Pasila railway area, Tikkurila railway station and Tampere railway station.

3.2 Vehicle speed

In all digital radio technologies, the network and terminal must synchronise themselves to encode and decode the data transferred between them.

The slower the terminal moves, the easier is the synchronisation, and the faster the terminal moves, the more challenging it is to keep the synchronisation.

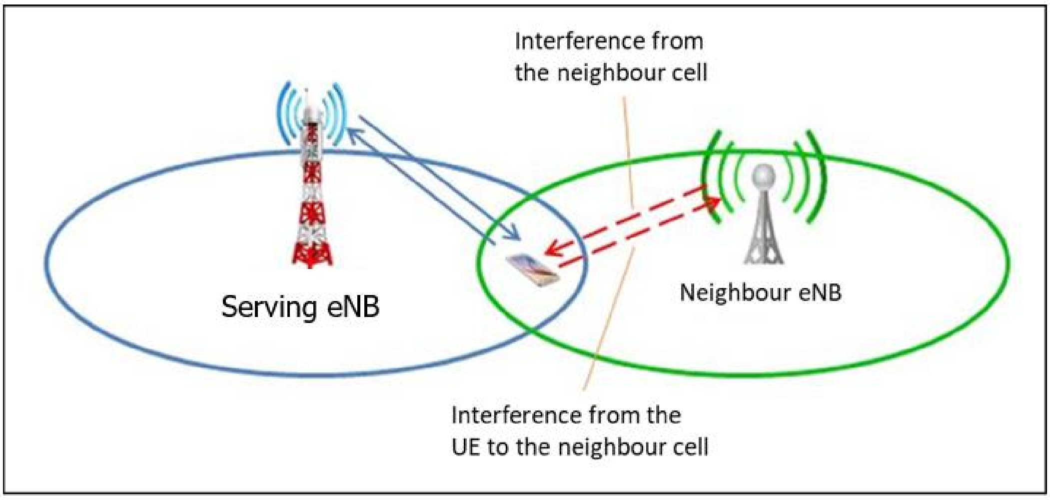
In GSM-R, the maximum vehicle speed is around 250 km/h and when this speed is exceeded, the network and terminal are not able to synchronise themselves. For 4G/5G technologies, the maximum vehicle speed is around 500 km/h.

When vehicle speed increases, the connection bandwidth typically decreases, because instead of bandwidth offering the terminals synchronise themselves more often.

3.3 Interference

There are numerous interference types defined in radio technology, such as the interference demonstrated in Figure 2. To make it simple: radio interference means a situation where the receiving terminal is exposed to unwanted radio frequencies. These unwanted frequencies cause reception disturbances and the desired signal is either weakened or lost.

In the case of mobile networks, interference is often the result of less-than-optimal radio network and frequency planning. Also, the reflections explained in section 3.1 may cause interference, since an unexpected frequency will be present in certain places as a result of reflection.



Picture source: http://howltestuffworks.blogspot.com/2016/02/inter-cell-interference-coordination_13.html

Figure 2. An example of interference.

Normally, MNOs dimension, plan and verify network capacity and coverage according to human beings; network coverage is measured from the height level of 1.5 metres to simulate pedestrians. Another way to make network measurements is to use drive tests, where the antenna is located at approximately the same height.

In the case of railways, the situation is a bit different. The receiver antenna is located at a height of 4.5 metres. Height difference may have an impact on the received signal level and it may also be more sensitive to interference in some circumstances.

3.4 Distance between the Base Station and User Terminal

Modern radio technologies like 4G and 5G use sophisticated methods when the data to be transferred is modulated to radio waves. Modulated data is transferred over radio waves as Symbols.

In 2G (GSM-R), one Symbol carries one bit. In 3G, one symbol carries 2 bits. In 4G and 5G, there are numerous modulation methods available and the bit amount per Symbol varies from 2 to 256 (and can be more).

Due to the laws of physics, the more bits are transferred with one Symbol, the faster the signal attenuates, and more energy is required to compensate for the attenuation. Due to this, the received bandwidth is very good when one is close to the Base Station. And when one is a significant distance away from the Base Station, the Base Station will use a modulation method coding less bits to Symbol and this can be seen as a narrower bandwidth.

In the case of railways, rural area tracks may have coverage challenges and long distances to serving Base Stations.

4 Base Values for Public Mobile Network Testing

4.1 ETCS Traffic Nature and Requirements

ETCS messages are bit-coded and strictly formatted, i.e., the delivered information is densely packed. How this coding is achieved, and which are the designated message formats, can be found listed in section 1.2.

In general, ETCS messages are mostly originated by OBU (downlink traffic) and received by RBC (uplink traffic). A minor part of the traffic is originated by RBC and received by OBU. The third category of ETCS traffic occurs between two RBCs when they negotiate an RBC-RBC handover. Uplink messages are smaller than the ones delivered downlink. For example, OBU may request Movement Authority (MA) and this message is small. The response RBC delivers downlink is MA, and this message may contain numerous optional fields and details concerning the assigned MA.

ETCS message content is transferred between OBU and RBC with a TCP/IP message payload field. The theoretical maximum size of a TCP message totals 65,535 bytes, but it is never available, since the used transport network limits the packet size with an MTU parameter which has a typical value of 1500 bytes. To avoid unexpected situations, the TCP packet size should never exceed the MTU limit. On the other hand, if the MTU is 1500 bytes, all possible ETCS message combinations can be carried between OBU and RBC with a single TCP message.

During the ERTMS/ETCS specification process (and GSM-R experiences), it has been estimated that ETCS traffic requires a bandwidth of 5 kb/s between OBU and RBC. Hence, a single OBU requires 5 kb/s net bandwidth for ETCS operations, but RBC requires N x 5 kb/s bandwidth, where N stands for the number of ETCS-controlled railway vehicles.

Since ETCS traffic is security-critical in nature, there are some additional requirements which should be emphasised:

A. Network reliability: every ETCS message sent should achieve its target both in the uplink and downlink direction.

B. Network availability: the used mobile network must guarantee the ability to carry ETCS traffic in all situations.

C. Network / connection stability in terms of traffic: ETCS traffic should be carried with a constant delay. The existing specifications allow for a long delay, and they do not define jitter in this respect, but the Digirail Radio Team sees a short delay and a small jitter as key factors. These values will be important in the future when the Moving Block system is in use and vehicle position information must be very accurate.

4.1.1 FRMCS decouples application and transport

When using GSM-R, the communication i.e., the transport stratum is linked strongly within the ETCS application communication. The ETCS application commands the modem to perform a Network Registration, change of network and other radio communication-related actions. When FRMCS is deployed, the modem is powered on and it performs a network registration. The used application will not know and does not control which radio connection or bearer is being used. The exact mechanisms in terms of how the interaction between on-board and trackside in different operational situations takes place is being specified particularly by the UIC FRMCS working groups.

4.2 Mobile Network Capacity and Performance Requirements

The Digirail Radio Team studied mobile network capacity and performance-related issues very carefully and detailed considerations are available in the document:

This document is the property of Fintraffic. Since the study is relatively long, only the conclusions are presented here. The following table (Table 1) indicates the requirements set for the mobile network connection and mobile network subscription, which is used for ETCS Traffic delivery (Source: *GENERAL_Digirail_CP_Testing_Public_Mobile_Networks Approved 1.0.pdf*).

Table 1. Radio network requirements for ETCS Traffic delivery

PARAMETER	TARGET VALUE	NOTES
RSSI	5 … 0	Receiving Signal Strength Indicator: the closer to 0 the value, the better.
RSRP	-100 dBm … -60 dBm	Reference Signal Received Power
RSRQ	-15 dB … -5dB	Reference Signal Received Quality
SINR	>=10 dB	Signal-to-Interference plus Noise Ratio
BER	10^{-9}	Bit Error Rate
Packet Loss	0.5% … 1%	
Latency	Less than 500 ms	
Jitter	Less than 20 ms	
GBR	50 kb/s	Guaranteed Bit Rate: operator defines this value in subscription data.

PARAMETER	TARGET VALUE	NOTES
Throughput	500 kb/s	Highest bandwidth allowed for the bearer. Operator defines this value in subscription data.
EPS Bearer	Used	Enhanced Packet Service (dedicated) Bearer with types QCI 65, QCI 84, QCI70, see also row "QCI".
ARP	In use	Allocation and Retention Priority
ACB	Not in use	Access Class Barring
QCI	In use	For test campaign a fixed operator specific QCI providing priority was defined for subscription by each MNO. QoS Class Indicators to be considered in future: QCI 65, QCI 84, QCI70

With these mobile network radio connection performance criteria (RRSI, RSRP, RSRQ, SINR, BER), the radio connection over the mobile network is satisfactory from ETCS' traffic point of view.

To guarantee the connection data transfer reliability and quality, the mobile network subscription used for ETCS traffic must fulfil certain QoS criteria (Latency, Jitter, GBR, Throughput, EPS, ARP, QCI).

4.3 Mobile Network Testing Base Values

The table below (Table 2) indicates the target values for both against Subset-093 (GSM-R) and FRMCS Draft SRS values. For Digirail, the target values are the same as the FRMCS Draft SRS values.

Table 2. Subset-093 (GSM-R) and FRMCS Draft SRS target values.

ITEM	SUBSET-093 REQUIREMENT	DIGIRAIL TARGETS (FRMCS DRAFT SRS VALUES)
Packet Service Setup Attach Delay PDP Context Activation	≤ 35 s (99%) ≤ 5 s (99%) ≤ 3 s (99%)	Altogether ≤ 10 s (99%)
Transaction Transfer Delay OBU Originated 100 Octets	≤ 2.6 s (99%)	≤ 500 ms (roundtrip)(99%)

ITEM	SUBSET-093 REQUIREMENT	DIGIRAIL TARGETS (FRMCS DRAFT SRS VALUES)
Transaction Transfer Delay RBC Originated 320 Octets	≤ 3 s (99%)	≤ 500 ms (roundtrip)(99%)
ETCS-DNS Lookup Delay	≤ 3 s (99%)	≤ 500 ms (roundtrip)(99%)
HTTP Request/Response	Not Defined	≤ 1 s (roundtrip)(99%)
IP Traffic Jitter (DNS, TCP, POS, MA)	Not Defined	≤ 20 ms
Packet Loss	Not Defined	≤ 1 %

Digirail also added target values for HTTP traffic, Jitter and Packet Loss which were not defined in Subset-093.

4.4 Multi-channel Router & Packet Duplication

Since a radio connection as a form of media transport is unstable, its stability and reliability can be improved by using many radio connections both in parallel and simultaneously.

With this arrangement, ETCS and RBC applications have a direct logical connection, but physically the connections are carried over separate physical bearers. This arrangement can be implemented with a multi-channel router multiplying IP Application packets for several physical transports (Packet Duplication), as shown in Figure 3.

There are several proprietary vendor-specific solutions on the market for packet duplication. For a standardised solution, at least two noteworthy options exist: TCP Extensions for Multipath Operation with Multiple Addresses (RFC 8684), commonly known as Multipath TCP, and Multipath Extension for QUIC (draft-ietf-quic-multipath-03), commonly known as Multipath QUIC. Even though Multipath QUIC is still at the draft stage, it may prove to be a more robust solution, as the QUIC protocol is designed to improve performance over the TCP protocol.

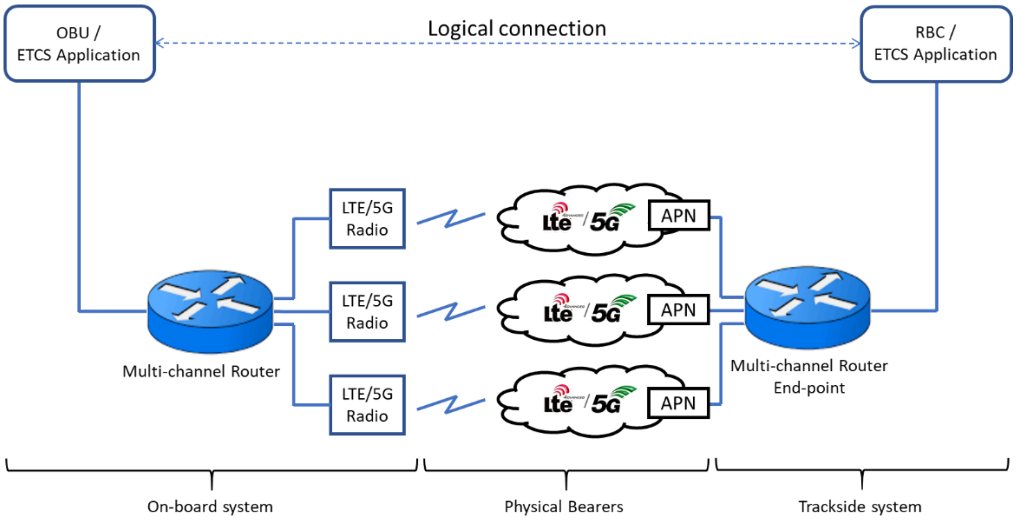


Figure 3. Multi-channel Router and Packet Duplication.

5 Testing Arrangements

5.1 Simulated ETCS Traffic

It was decided to utilise simulated ETCS traffic when testing public mobile networks, since its characteristics are well known and this method simulates real-life situations as accurately as possible.

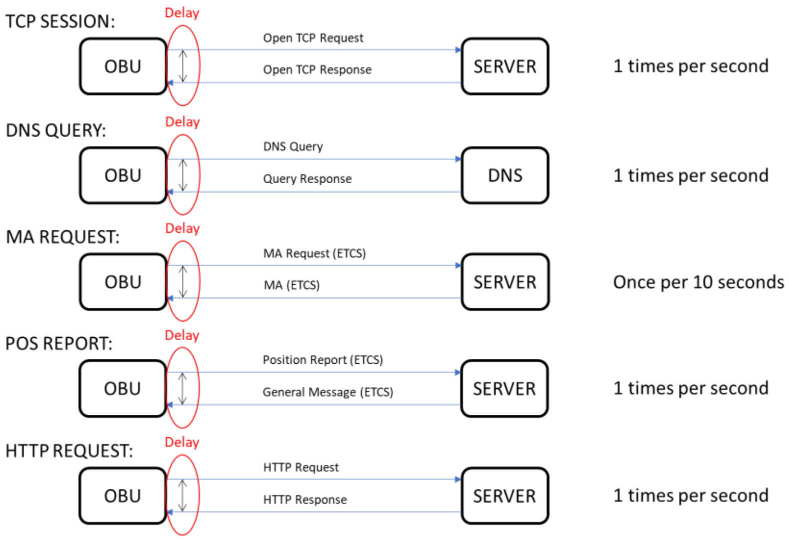


Figure 4. ETCS traffic scenarios used in mobile network testing.

To generate enough traffic with the selected procedures, they are frequently repeated (Figure 4). ETCS messages have dummy content but the correct lengths. Since Subset-026 does not define any acknowledgement mechanism for a Position Report, a General Message was added as acknowledgement to measure delay.

Delay values collected during the testing are compared to the values listed in the table in chapter 4.

5.2 Measurement System

Digirail Radio Network Testing combines several measurement items under a single testing program, as detailed in Figure 5.

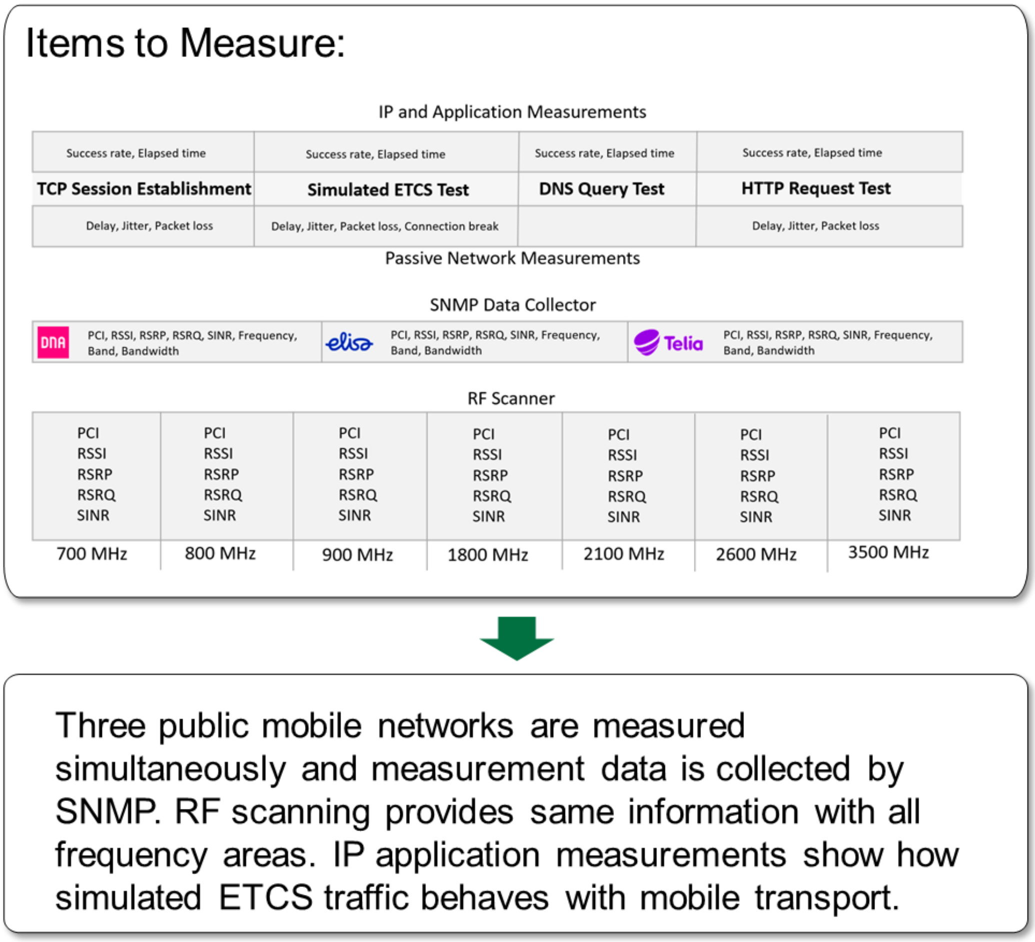


Figure 5. Items to be measured.

The IP and Application measurements aimed to verify that simulated ETCS traffic with some additional items functions within the limits defined in section 4.3. This measurement also gives once-per-second snapshots of the related radio parameters (RSRP, RSRQ) of the three measured public mobile networks.

At the same time, RF scanning provides additional information of the three public mobile networks, their frequency areas and radio connection parameters.

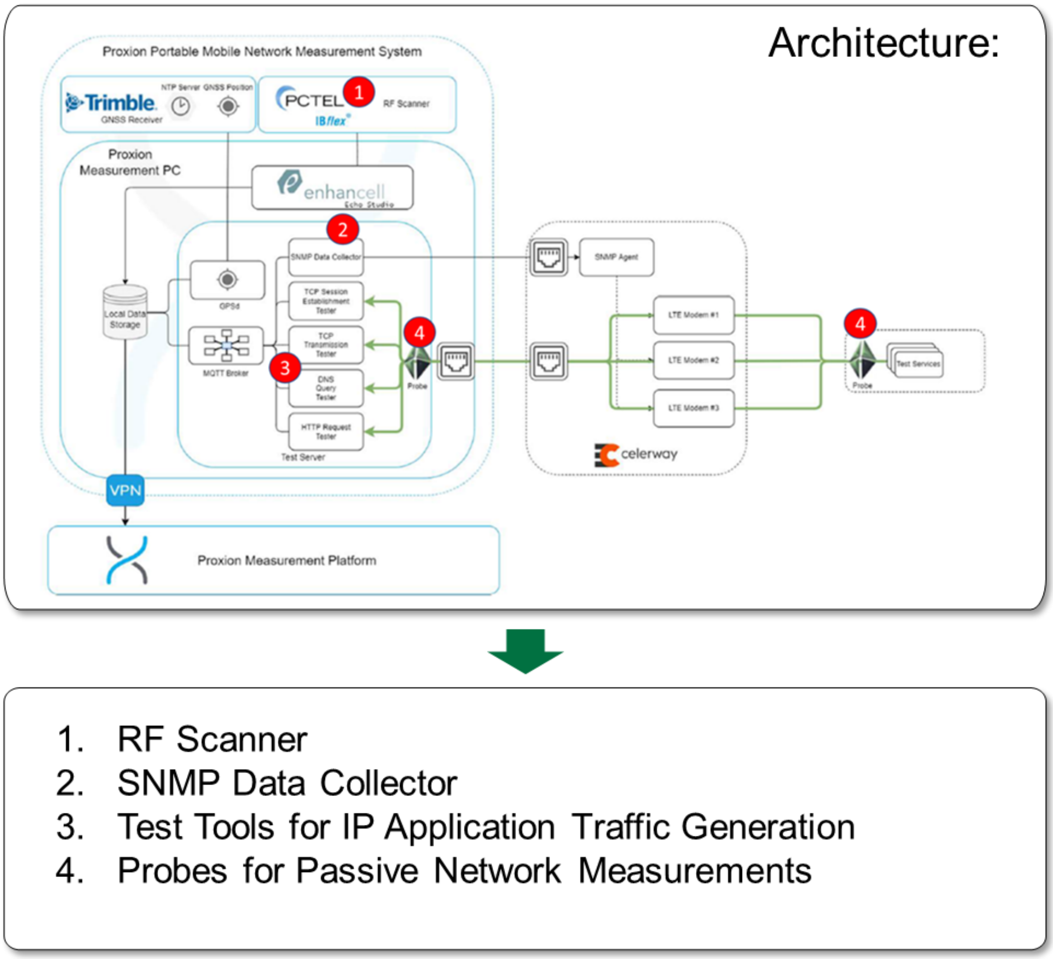


Figure 6. Measurement system architecture.

The Proxion portable network measurement system (Figure 6) integrates together all the necessary equipment required for the measurements:

- Trimble GNSS receiver for positioning information: all transactions have positioning information included
- Enhancell Echo Suite and various testers for traffic generation
- Kaitotek probes for passive network measurements.

The datasheet and information links are found in section 8 ([1] and [4]).

The multi-channel router is provided by Celerway. It has 3 slots for SIM cards and this router supports all traffic types from 2G to 5G. Like many other multi-channel router suppliers, Celerway also has a proprietary solution to implement IP traffic multi-channel routing. The Celerway solution is called Phantom VPN. In multi-path mode (Celerway names it *Diversity Mode*), incoming IP packets are triplicated to use all radio modems simultaneously. The other end of the connection furnishes the Phantom VPN endpoint, aggregating incoming traffic.

It should be emphasised that the above-described solution is a Celerway-specific implementation of packet duplication.

The datasheet and information links are found in section 8 ([2]).

5.3 Antennas & Installation

The antenna being used in the testing is especially designed for railway use: Kathrein Train Antenna 694–6000 MHz and GNSS (GPS, GLONASS, BEIDOU, GALILEO) 87010032. In addition to the antenna, Low-noise Amplifiers GNSS (GPS, GLONASS, BEIDOU, GALILEO) 86010142 were used.

Three Kathrein antennas were located on the rooftop of the measurement vehicle and were placed 1-1.5 metres mutual distance from each other, as shown in Figure 7. Each antenna was provided with a low-noise amplifier and cabling was linked to the personnel premises located in the central part of the measurement vehicle. Also, the Measurement System and Celerway Arcus multi-channel router were installed in the personnel premises of the vehicle.

Figure 7. Rooftop view of the Measurement Vehicle.

Separate GNSS and RF scanner antennas were also installed on the roof of the measurement vehicle. All antennas were placed at an average height of 4.45 m from the track level.

The datasheet and information links can be found in section 8 ([3]).

5.4 Connections

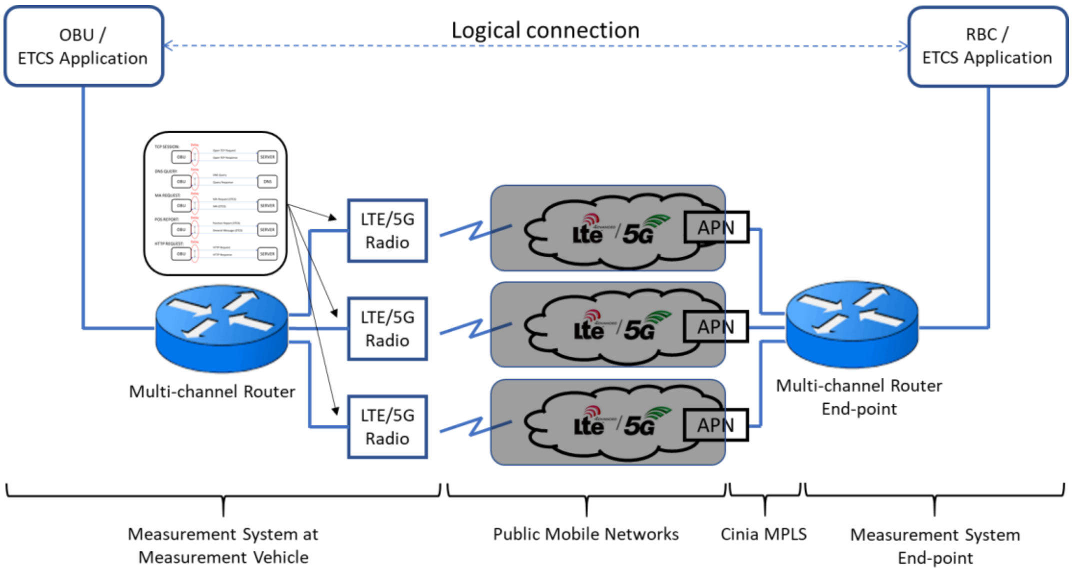


Figure 8. Mobile networks are treated as Black Boxes.

ETCS traffic measurements were implemented as per Figure 8 above. The OBU/ETCS Application was replaced with a Measurement System Traffic Generator and Probe. The Measurement System Endpoint was a server offering TCP, HTTP and DNS services and an acknowledgement mechanism for ETCS messages.

The Measurement System delivered scripted traffic to the multi-channel router which in turn triplicated the traffic to radio modems containing the public mobile network subscriptions with pre-defined parameterisation (see section 4.2).

The Celerway Arcus multi-channel router had three prioritized network subscriptions simultaneously that were provided by the Mobile Network Operators. The prioritization of the subscriptions ensured service regardless of the capacity utilization levels of the serving cell.

The multi-channel router has three operating modes with Phantom VPN and two of these were used in this testing program. The first testing round was performed with Phantom VPN operating mode *Best Quality*. In this mode, all available networks are used simultaneously, and the traffic is load balanced per flow based on throughput estimates.

The second testing round was done with Phantom VPN operating mode *Diversity Mode*. This mode uses Phantom VPN to triplicate the traffic and the traffic is sent through all connected networks simultaneously. On the Phantom VPN receiving end the traffic that arrives first is processed and the rest is discarded.

Public mobile networks were treated as black boxes and only offered the transport service for ETCS traffic. Each public mobile network had a private APN where to route the measurement traffic. Cinia connected these APNs to the Measurement System Endpoint through its own MPLS network. No measurement traffic was routed through the Internet.

6 Test Results

In all measurements, the multi-channel router radio modems were locked to 4G/LTE operating mode, since 5G coverage was available only in very selected areas, typically covering railway stations and urban areas.

A similar type of measurement program is planned to be repeated when 5G technology coverage is better throughout larger geographical areas of the railway network.

6.1 Testing Area and Scope

The Finnish State Rail network length is approximately 6,000 km, and the target was to measure all relevant sections of the network. As per defined, the measured track sections consisted of Operational Level 1 track sections (all tracks which are under the control of the Fintraffic Traffic Management Centre). Due to the nature of the railway network, the total length measured was around 8000 km.

The entire network was measured first with router operation mode *Best Quality* and then the second round was made with router operation mode *Diversity Mode* with selected track sections (length approx. 2000 km).

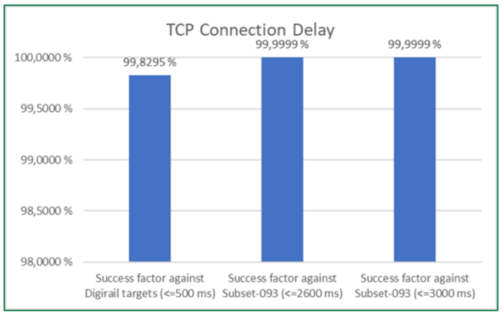
The only track section which was not possible to measure was between Kajaani and Ämmänsaari due to track maintenance works. The length of this track section (Kontiomäki-Pesiökylä-Ämmänsaari) is 93 km.

A map of the Finnish State Railway Network can be downloaded from the address:

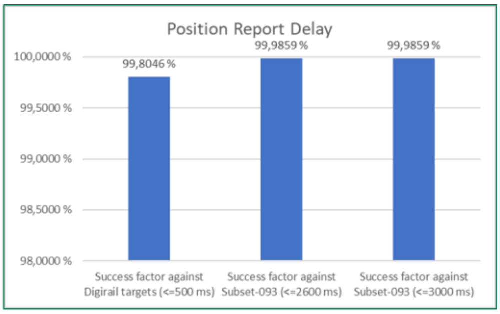
https://vayla.fi/documents/25230764/47264414/Rataverkko_01012021.pdf/2d56780c-9d86-8695-02b5-37031b9e69d8/Rataverkko_01012021.pdf?t=1608032206939

6.2 Test Results in Best Quality Mode (8,000 km)

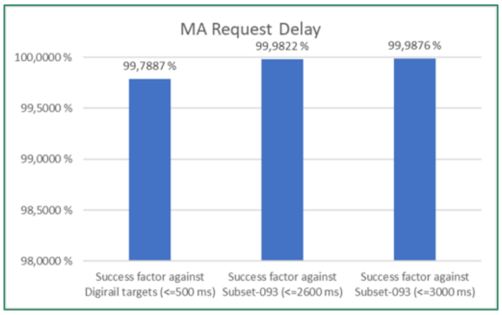
The following graphs show how the traffic types presented in section 5.1 behaved in public mobile networks.



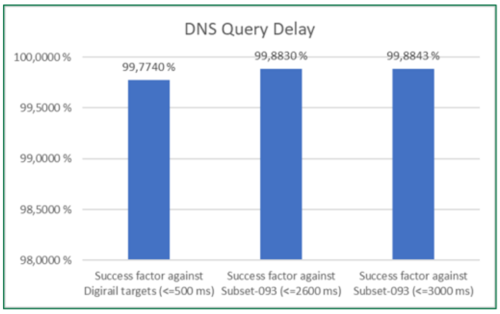
Total Samples	705613
Jitter (ms)	15,62
Average Delay (ms)	60,20



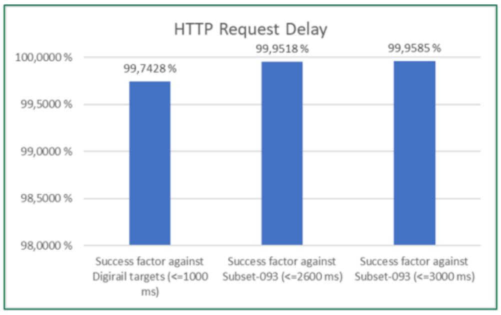
Total Samples	688444
Jitter (ms)	18,45
Average Delay (ms)	83,35



Total Samples	72870
Jitter (ms)	21,54
Average Delay (ms)	107,30



Total Samples	715549
Jitter (ms)	18,36
Average Delay (ms)	67,11



Total Samples	676506
Jitter (ms)	23,31
Average Delay (ms)	119,75

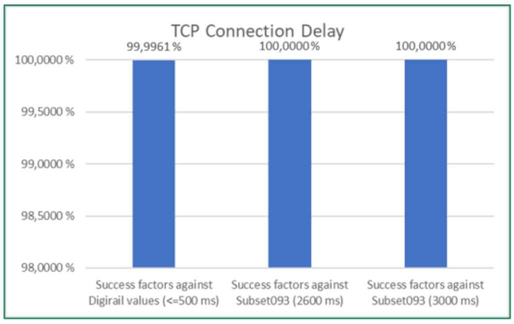
Figure 9. Test Results – Best Quality Mode.

Based on the results demonstrated in Figure 9, both the Subset -093 tolerance level and the Digirail delay threshold of 500 ms or better ("Critical Data Legacy Applications", 3GPP TR 22.989 V18.5.0) were met with a success rate of more than 99%.

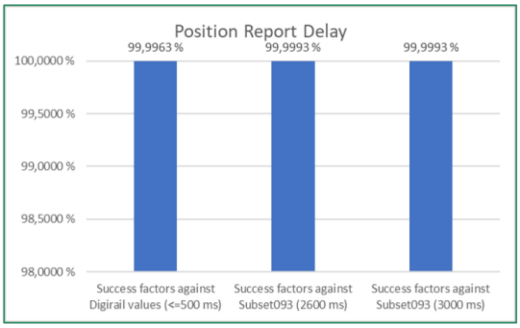
During the testing, it was noted that all traffic produced irregularly delayed spikes (which is indirectly present in Jitter values). This was somewhat expected and is due to the Phantom VPN operating mode: since in *Best Quality* operation mode all traffic is load balanced per flow over all networks. The used radio network connection for the specific flow may change, or even drop in terms of quality, and therefore, the multi-channel router is not necessarily using the best network when delivering ETCS traffic.

Conversely, the *Best Quality* operation mode exposes possible mobile network challenges more easily. As the figures above suggest, no remarkable issues were present in mobile networks.

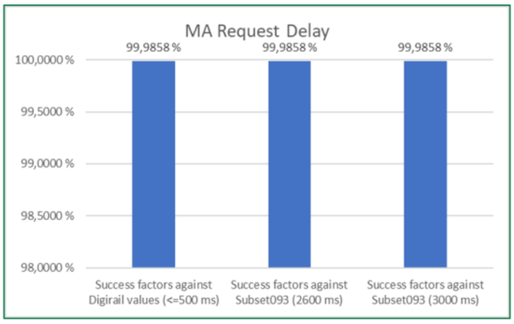
6.3 Test Results in Diversity Mode (2,000 km)



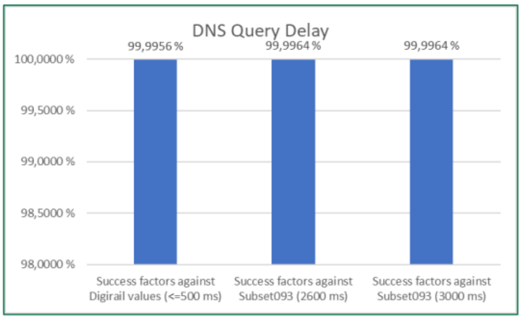
Total Samples	128927
Jitter (ms)	5,92
Average Delay (ms)	36,66



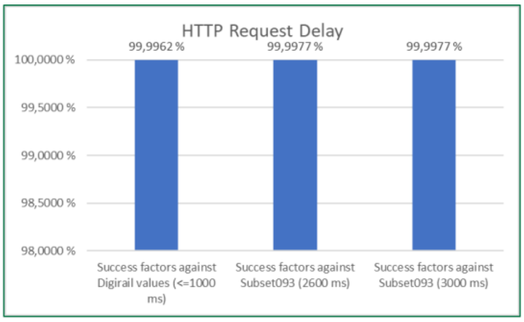
Total Samples	133352
Jitter (ms)	7,76
Average Delay (ms)	67,06



Total Samples	14043
Jitter (ms)	10,71
Average Delay (ms)	90,64



Total Samples	137764
Jitter (ms)	6,97
Average Delay (ms)	43,08



Total Samples	132937
Jitter (ms)	9,06
Average Delay (ms)	80,99

Figure 10. Test Results – Diversity Mode.

As was expected, simultaneous ETCS traffic performed over three mobile networks stabilised the traffic. This is visible in Jitter values which are considerably smaller. Some decrease is also present in average delay values.

In other words, three physical bearers serve the logical connection of the ETCS traffic much better in terms of delay, jitter, and reliability.

Similarly, the *Diversity Mode* results illustrated in Figure 10 fulfilled both the Subset -093 tolerance level and the Digirail delay threshold of 500 ms or better ("Critical Data Legacy Applications", 3GPP TR 22.989 V18.5.0) and were met with a success rate of more than 99.9%. Moreover, the Jitter limit is also now clearly exceeded in all traffic types.

6.4 Test Results Against TR 22.889 and TR 22.989

3GPP TR 22.889 (*Study on Future Railway Mobile Communication System (FRMCS)*) and 3GPP TR 22.989 (*Study on Future Railway Mobile Communication System*) define the following limits:

- Legacy applications Critical Data Transfer latency <= 500 ms and reliability 99.9%
- Future applications Critical Data Transfer latency <= 100 ms and reliability 99.9999%

When test results are compared against these limits, the situation is as follows:

Table 3. Test Results Against TR 22.889 and TR 22.989.

TCP	OK /500 ms	OK /100 ms
Total Samples: 128927	128922 Pcs	128892 Pcs

POS	OK /500 ms	OK /100 ms
Total Samples: 133352	133347 Pcs	132556 Pcs

Success %	99.9961 %	99.9729 %
Average Delay	36.6581 ms	36.6581 ms

Success %	99.9963 %	99.4031 %
Average Delay	67.0636 ms	67.0636 ms

DNS	OK /500 ms	OK /100 ms
Total Samples: 137764	137758 Pcs	137720 Pcs
Success %	99.9956 %	99.9681 %
Average Delay	43.0819 ms	43.0819 ms

HTTP	OK /500 ms	OK /100 ms
Total Samples: 132937	132932 Pcs	121896 Pcs
Success %	99.9962 %	91.6946 %
Average Delay	80.9911 ms	80.9911 ms

MA	OK /500 ms	OK /100 ms
Total Samples: 14043	14041 Pcs	11870 Pcs
Success %	99.9858 %	84.5261 %
Average Delay	90.6373 ms	90.6373 ms

As Table 3 values suggest, test results are fully compliant for the defined Legacy Applications requirements. Once the future application requirements have been defined, some additional network investments might be required.

6.5 Delay Iteration – Multi-channel Router Best Quality Mode

Since sections 6.2, 6.3 and 6.4 indicated that public mobile networks can handle ETCS traffic both reliably and robustly enough, we changed the situation vice versa by setting a question: what is the minimum delay value to achieve 99% (Subset-093 requirement) and 99.9% (UIC limit value) reliability?

When calculating the samples in multi-channel router *Best Quality* operation mode, the results are equivalent to that seen in Table 4:

Table 4. Delay Iteration Values in Best Quality Mode.

	Subset-093	UIC
TCP	120 ms	>500 ms
MA	180 ms	>500 ms
POS	160 ms	>500 ms
HTTP	140 ms	>500 ms
DNS	120 ms	>500 ms

According to these calculations, Subset-093 99% limit value is achieved with reasonable delay values which are less than 500 ms. For UIC limits, this operation mode is not satisfactory, and UIC limit value 99.9% was achieved with delay values being measured as between 500 and 1000 ms.

6.6 Delay Iteration – Multi-channel Router Diversity Mode

The question is the same as in the beginning of the section 6.5, but here the multichannel was used in *Diversity Mode* operation mode.

Table 5. Delay Iteration Values in Diversity Mode.

	Subset-093	UIC
TCP	60 ms	80 ms
MA	130 ms	150 ms
POS	100 ms	120 ms
HTTP	120 ms	140 ms
DNS	70 ms	90 ms

Like Table 5 suggests, all traffic types had less than 500 ms delay when compared against Subset-093 and UIC limits.

7 Conclusions

Based on the test results presented in section 6, some conclusions can be made.

In terms of capacity and coverage:

- The 50 kb/s capacity and coverage were received on the whole network, except for five spots close to the Russian border.

In terms of reliability:

- The Finnish mobile networks fulfil the ERA/Subset-093 requirements even in *Best Quality* - mode as well as the FRMCS SRS draft values. In *Diversity Mode*, the reliability is as high as **99.986%,** clearly exceeding the 99.9% requirement. The 99.9% reliability is achieved even if the allowed delay, instead of 500 ms, is reduced to as low as **150 ms**.

- On 95.31% of the railway network, all three operators' signals were simultaneously above -110 dBm, and in **98.32%** of the railway network at least two operators' signals were simultaneously above -110dBm. This means that the connection is very resilient against telecom equipment failures.

Overall:

- The measured performance and latency have proven that by using a suitable multi-channel router, the railway requirements are met when using public mobile networks.

- Despite the potential challenges described in Section 3, the measurements were successful and the results excellent.

8 References

This section contains reference links classified by items / entities.

[1] Proxion Measurement System equipment data sheet information:

PCTEL IBflex RF-scanner (SW: 3.8.1.0): https://www.pctel.com/products/test-measurement/scanning-receivers/ibflex-scanning-receiver/ Brochure: https://d3dqzy9ky05fbv.cloudfront.net/wp-content/uploads/2020/07/IBflex-Brochure-web.pdf

PC: Advantech UNO-148, Win 10 Enterprise LTSC: https://advdownload.advantech.com/productfile/PIS/UNO-148/file/UNO-148_DS(092821)20211111094917.pdf

Echo Studio sw 3.2.34 (with special feature to start and stop measurements from outside of Echo studio): https://enhancell.com/enhancell/products/echo-studio-2/

Cisco RV345P router (SW: 1.0.03.15): https://www.cisco.com/c/en/us/products/collateral/routers/small-business-rv-series-routers/datasheet-c78-742350.pdf

Teltonika RUTX11 3G/4G/LTE modem (SW: RUTX_R_00.02.06.1): https://teltonika-networks.com/downloads/en/rutx11/RUTX11_Datasheet-v1.1.pdf

GNSS: Trimble BX992 (SW: 6.10) Accuracy 30cm: https://info.intech.trimble.com/bx992-datasheet

https://ecatalog.hubersuhner.com/media/documents/datasheet/en/pdf/84459531

Disclaimer: some of the links may not work due to site and product structure changes implemented by the vendor.

[2] Celerway Arcus multi-channel router datasheet and information:

https://creatorapp.zohopublic.eu/file/crm_stamp/cw-partner/Product_Specification/101006000000298021/File_upload/download/gbN5Q5Hdd5vyZpN2umb1wOtZvHrWdC4bhg83ze7FVUP5gTE7Mvkrf8jkxg0kSeVgkYOk2g4rGbUCKBu6xtbVMTRnuxrYe3P2S9Dg?filepath=/1657777581774_ARCUS.pdf

https://creatorapp.zohopublic.eu/export/crm_stamp/cw-partner/pdf/Components_ARCUS/TG9z8Cq8a1sSjt7dqxVHmssXvHyRmTVfK70gtSjNmf0TPKA6gkF2DD9jhfRtrKuGKp8PPVTv75Td6fnw6K2gDxwh9CBC6h9hHVSH

Disclaimer: some of the links may not work due to site and product structure changes implemented by the vendor.

[3] Kathrein antenna and low-noise amplifier data sheet and information:

https://ecatalog.hubersuhner.com/media/documents/datasheet/en/pdf/84459531 https://www.mouser.fi/datasheet/2/829/HU-BER_2bSUHNER_87010032_DataSheet-3000423.pdf

Disclaimer: some of the links may not work due to site and product structure changes implemented by the vendor.

[4] GNSS and RF Scanner antenna data sheets and information:

https://geospatial.trimble.com/sites/geospatial.trimble.com/files/2019-03/Datasheet%20-%20Trimble%20Zephyr%203%20GNSS%20Antennas%20-%20English%20USL%20-%20Screen.pdf

https://s3-eu-west-1.amazonaws.com/cdn.webfactore.co.uk/5183_pctel-antennas-for-scanning-receivers-brochure-revc-june2021-web.pdf

Disclaimer: some of the links may not work due to site and product structure changes implemented by the vendor.

Finnish Transport
Infrastructure Agency

ISSN 2490-0745
ISBN 978-952-317-016-6
www.vayla.fi